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Status of Neutron Imaging - Activities in a Worldwide Context

Eberhard H. Lehmann^{a*}, Danas Ridikas^b

^aPaul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

^bInternational Atomic Energy Agency, PO Box 100, A-1400 Vienna, Austria

Abstract

We report on the status and the visible progress in neutron imaging technology based on the installation of new facilities world-wide, on the further upgrade of existing ones and on the new aspects with respect to methods and applications. This overview is based on existing databases from the IAEA and a new questionnaire-based data collection driven by ISNR and IAEA. As a result of our analysis, 50 facilities can be categorized into either “user facility”, “in-house usage”, “under installation” or “project”. The potential for further increase of the number of facilities is seen in countries with underutilized research reactors with powers above 1 MW, mostly in Eastern Europe or other developing countries. As well, the future trends of advanced methods in neutron imaging and their development in a few laboratories world-wide are described. A permanent exchange of knowledge and experience among the involved experts has been organized by the workshop series NEUWAVE since 2008, on about a yearly basis.

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1. Introduction

The event of a World Conference on Neutron Radiography (WCNR), which occurs only every four years, is a good opportunity to describe the state-of-the-art in the technology and to deliver an overview of the current situation in the field. Because the utilized neutron sources are essential for the performance of a neutron imaging facility, we instituted a joint investigation by the International Society for Neutron Radiology (ISNR) [1] and the

* Corresponding author. Tel.: +41-56-310-2963; fax: +41-56-310-3131.
E-mail address: Eberhard.lehmann@psi.ch

International Atomic Energy Agency (IAEA) [2] using existing data resources and implementing a questionnaire-driven new world-wide overview of facilities.

Neutron imaging activities have been progressed in recent years from a tool for non-destructive testing to more sophisticated research methods for many kinds of investigations and applications. For this reason, a further improvement and creation of different features was needed, mainly based on the digital data output of the results. However, this process happens only in a limited number of laboratories where a user program of scientific partners has been established. On the other hand, attempts occur to initiate and implement new imaging facilities at prominent strong sources or at sources which are under design or construction such as spallation neutron sources. The role of developing countries with their newly installed (or under consideration) sources will be mentioned separately.

It is intended in this paper to provide a picture of the current situation in the field of neutron imaging with respect to the individual imaging facilities world-wide and the development of new methodical approaches and challenges. We also describe which application fields have been opened for the scientific and industrial usage of neutron imaging technologies.

Neutron imaging cannot only be seen as isolated, but also in the context of neighbouring fields, where a strong impact and interaction can be shown. This situation is schematically represented in Fig. 1.

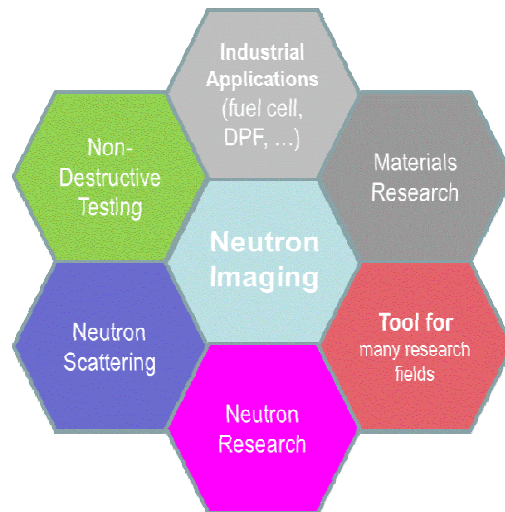


Fig. 1: Symbolic description of the related fields next to “neutron imaging”, where synergies and interaction can be identified

The initiatives by the IAEA for better utilization of neutron sources, mainly research reactor based, will be highlighted, current activities will be mentioned, and first outcomes will be referenced. The collected data on neutron imaging facilities are made available to enable potential users an access to the nearest options for the utilization of the method.

2. Neutron Sources suitable for imaging

Most of the neutron imaging facilities are designed and built in a manner with a simplified illustration given in Fig. 2, where the beam from an initial source of fast neutrons, after moderation and filtering via a collimator and some other beam tuning devices, is extracted towards the sample position. As the transmission image is recorded in

most of the applications, the 2-dimensional image detector is placed just behind the sample before the residual beam reaches a beam dump.

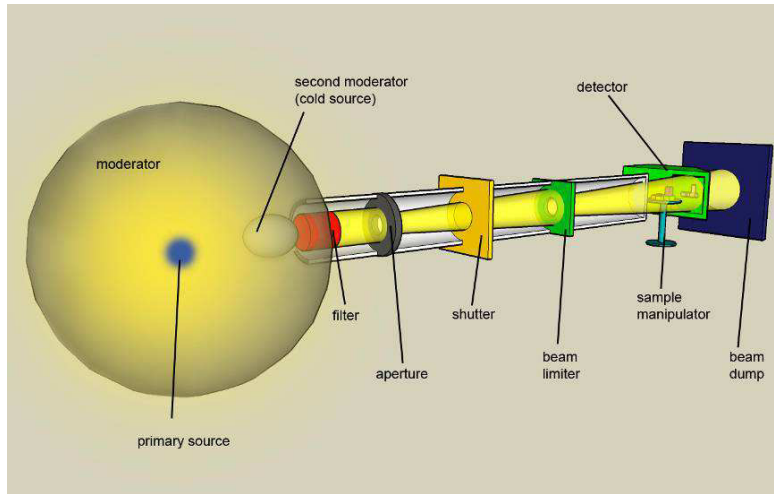


Fig. 2: Schematic outline of a typical neutron imaging facility for thermal or cold neutrons

It is clear that such a facility has to be surrounded by adequate shielding to fulfill the radiation protection requirements, including a system for controlled access. Next to these basic components, there are some new features with advanced properties for dedicated beam tuning:

- Energy selective devices (turbine, filters, double-crystal mono-chromatizer, TOF options, etc.) to limit the spectral range for better quantification and structural analysis;
- Polarizers, to sort out only one spin-state;
- Collimators (e.g. Micro-Channel-Plate type) to enhance spatial resolution and to suppress the contribution of scattered neutrons behind a sample;
- Grating interferometers, to measure phase properties or “dark field” images;
- Secondary detectors (for scattered neutrons), as a complement to the transmission data acquisition; and an
- X-ray source (for comparison), to enable fusion between different data sets.

Although quasi-mobile neutron sources based on particle accelerators exist, almost all neutron imaging stations are located at strong neutron sources (research reactors or spallation neutron sources). Only in this way, high spatial and time resolution can be acquired with the flexibility needed and at a reasonable measurement time for advanced imaging techniques.

3. The IAEA Research Reactor Data Base

For neutron imaging purposes, thermal and cold neutrons are preferred and common. The beam line should have direct access to the peak flux region. An overview about research reactor based facilities can be extracted from the IAEA Research Reactor Data Bases (RRDB): <http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx>

The RRDB indicates that 247 reactors are in operation, with 6 under construction and 12 planned. Together with 4 spallation sources operating, a total of 269 neutron sources exist world-wide. However, only 116 research reactors have a power of more than 1 MW, while at the same time 152 are older than 40 years.

A detailed search about the research reactor utilization for “neutron radiography” reveals only 72 facilities as such, with 2/3 of them situated in developing countries. On the other hand, only 52 sites declare involvement with

“neutron scattering” activities. This is somewhat surprising since the neutron scattering community is much larger, much more active and one would expect them to be better represented around prominent sources than the neutron radiography community presently. Another statistic might be interesting in this context: research reactor sites with “high utilization” count for only 42 in this database! These facilities are distributed as shown in Fig. 3.

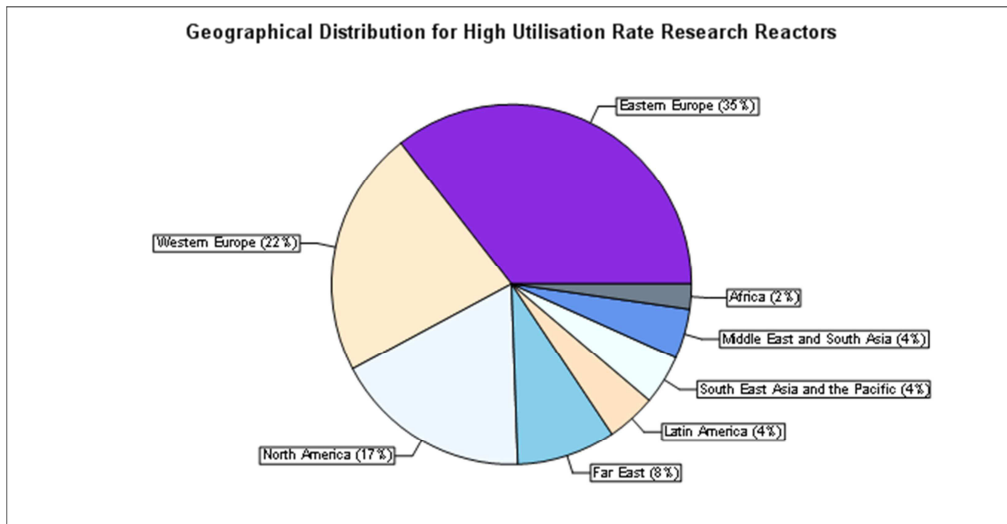


Fig. 3: Research reactor usage in the global context (data taken from [3])

Based on these considerations of neutron sources, we assess that the potential for further installations for neutron imaging remains high. However, a driving force on-site and an adequate budget are needed to implement the required infrastructure and to start a research program associated with neutron imaging.

4. Neutron Imaging facilities world-wide

Based alone on the neutron source descriptions, it is impossible to have a complete picture of the neutron imaging facilities and activities in a world-wide context. We have to distinguish between the option to obtain single images on film (one per hour) and a highly equipped user laboratory with expertise not only in image taking but also in image processing and quantitative data treatment. In addition, some categories are needed to rank the very different facilities in the right manner in order to judge their performance adequately.

4.1. The ISNR-IAEA data base of facilities

The International Society for Neutron Radiology (ISNR) [1] was created in 1996 in order to organize regular meetings of experts active in the field, either as operators or as users of neutron imaging facilities. The series of “World Conferences on Neutron Radiography (WCNR)” took place in 2014 for the 10th time, with an interval between the conferences of about 4 years. Meanwhile, the series of “International Topical Meetings on Neutron Radiography” were held in years between WCNRs since 1990, with a total of seven so far. The ISNR has now more than 200 members and provides activities other than conference organization (e.g. homepage, newsletter, announcements, networking).

Based on this organization and contact with the involved facilities’ operators, a questionnaire was created and distributed to ISNR members and to IAEA partners. As a result, it contains current information on the parameters of the facilities and the responsible persons. If desired, a future survey might be undertaken to provide more details of individual facilities.

4.2. State-of-the-art in neutron imaging

It was found that each facility is unique and built individually. However, there is a need for comparison using criteria which have to be derived to provide measuring parameters common for facilities today.

Here, we summarize some conditions and parameters which can be used for evaluation of facilities:

- Dedicated beam line at a (most) powerful neutron source: high intensity is required for either high temporal or spatial resolution; any sharing of beam ports is often accompanied by compromises and conflicts;
- Well defined thermal or cold spectrum: this knowledge is a prerequisite for precise quantifications since the cross-section data are strongly energy dependent;
- Best possible beam collimation ($L/D > 100$): otherwise, the spatial resolution is inherently limited by beam blurring;
- Reasonable large field-of-view (diameter > 10 cm) – homogeneously illuminated: this allows inspecting even extended objects;
- Digital imaging detection system: this enables short acquisition time, low activation, and easy data transfer and advanced imaging procedures;
- Experimental infrastructure (e.g. remote control of processes, radiation protection, access control, ...)
- Preparedness for hosting internal and external users

Although further conditions and parameters might be added on demand, these current ones will be used for a trial of classifications as done below.

4.3. Classification of facilities

Because there are huge differences in the performance of the facilities declared as performing neutron imaging, we separate them into four categories:

- **User** facilities: operate for external research partners as well; the infrastructure and the detection systems are at a state-of-the-art level; research proposals are evaluated by an independent panel; results are published at an adequate scientific level;
- In-house usage: the facility might have high performance, but the access from external users is not (yet) organized and foreseen;
- Under installation: the system is not yet completed;
- Projects: a facility is planned, but the installation has not yet started.

Using the provided data from 50 different facilities, we sorted their properties according to these four categories. The results are shown in Fig. 4. In this collection, we already included facilities and projects which came into operation recently. Here, we mention new installations explicitly with some comments on their status.

1. **Australia**, DINGO at OPAL reactor: This thermal beam line facility is nearly completed and ready to start user operation after the commissioning is certified by the authority.
2. **Germany**, PONTO-2 at BER-2 reactor, HZB Berlin: It is built for imaging with polarized neutrons using polarizer/analyzer pairs for the depolarization analysis in a mono-chromatized beam.
3. **Russia**, imaging station at IBR-2 pulsed reactor, JINR Dubna: Using the strong pulses at this 2 MW reactor, the performance for energy selective imaging in TOF mode might be good; until now, only “white beam” images have been taken.
4. **UK**, IMAT at ISIS-TS 2 pulsed spallation source: The external building and some components are already on place; first trials with imaging detectors are planned for 2015.

5. **France**, IMAGINE at ORPHEE reactor in CEA Saclay: This approach is user driven since no real neutron imaging facilities exist in France anymore. At the end of a guide for cold neutrons, there is a simple detection system installed for routine work like explosives inspection.
6. **China**, Two facilities are planned at the 60 MW CARR research reactor in CIAE Beijing, one for thermal the other for cold neutron applications.
7. **Japan**, RADEN at JPARC pulsed spallation source. It is under installation and planned to be ready in 2015.
8. **USA**, VENUS at SNS pulsed spallation source: It is under development and will be installed as soon as the financing is guaranteed.
9. **USA**, NIST, a cold beam line for imaging, It is under installation which complements the well-used thermal facility at the 20 MW reactor NBSR.
10. **European Union**, ODIN at ESS pulsed spallation source: It is among the three first-day facilities to be installed as soon as the whole source will be set up (beyond 2020).
11. **Germany**, An upgrade of the cold facility at the BER-2 reactor guide (HZB) in Berlin (CONRAD-2).
12. **Germany**, An upgrade of the cold neutron imaging station at FRM-2 in Munich/Garching (ANTARES-2).

All these projects will certainly influence further method development and user applications in various fields.

The global overview on installations and some main parameters can be found via the following link: <http://tinyurl.com/neutronmap> - which is under permanent update.

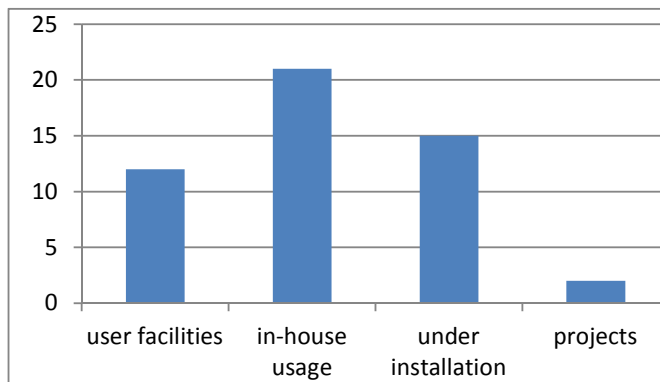


Fig. 4: Neutron imaging facilities world-wide according to their usage and performance; data are based on an ISNR/IAEA questionnaire answered by ~50 facility operators world wide

4.4. Initiative and supports by IAEA

The IAEA continuously supports and provides assistance to its Member States in the area of utilization and applications of research reactor based neutron sources. There are many relatively recently installed research reactors in developing countries with the potential to implement neutron imaging capabilities. Next to the technical installations, there is also a need to train the operators and potential users in an adequate way. Here, we list some of the performed and planned activities:

- Coordinated Research Project on “Application of Two and Three Dimensional Neutron Imaging with Focus on Cultural Heritage Research” (2012-2016)
- IAEA training workshop on “Advanced Use of Neutron Imaging for Research and Applications”, held in August 2013 in Berlin (Germany) hosted by HZB
- IAEA Round Robin tests initiative, in cooperation with PSI, for contrast and resolution (2012-2013)

- The IAEA Technical Meeting on “Regional Research Reactor Users’ Networks (RRUNs): advances in neutron imaging”, held in November 2012 in Jakarta (Indonesia)
Technical Meeting on “Research Reactor Users’ Networks (RRUNs): Standardization of Neutron Imaging for Industrial Applications” held in June 2014 in Vienna (Austria)
- Continuation of IAEA Round Robin tests, in cooperation with PSI and with new samples (during 2015)
- IAEA training workshop on “Advanced Use of Neutron Imaging for Research and Applications”, planned to be held in September 2015 in Villigen (Switzerland), hosted by PSI
- Initiation of a new Coordinated Research Project on “Development of Standardized Protocols and Samples to Evaluate the Performance of Digital Neutron Imaging for Industrial Applications”; start is expected in 2016

These activities are open to the IAEA member countries and are/will be communicated via the official channels.

5. New trends in neutron imaging techniques and applications

Driven by the progress in X-ray imaging (e.g. synchrotron light facilities, X-ray tube based systems, etc.), where a high degree of spatial and temporal resolution is being exploited for many research purposes, neutron imaging is being pushed forward as well. Although neutron sources are much more limited in intensity than photon sources, suitable setups can be used to make particular improvements and to utilize the neutrons as best as possible, as illustrated in Fig. 5.

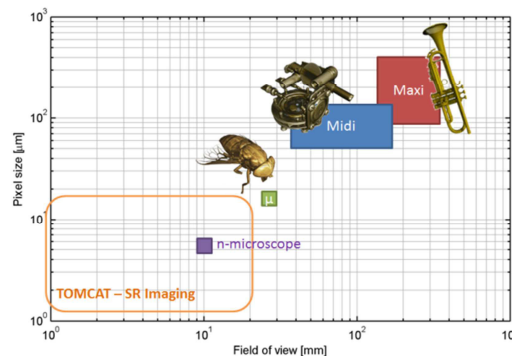


Fig. 5: Typical working range of detector setups at PSI with respect to FOV and pixel size, including the running micro-setup [4] (μ) and the n-microscope which is under development

- Higher spatial resolution: The neutron microscope project [5] intends to reach a spatial resolution better than 10 μm by optimizing optics, scintillators and camera performance. Alternative concepts are the use of Wolter neutron optics [6] for magnification by focusing/defocusing of the beam or the centroiding in the readout of pixel detectors.
- Better and adequate time resolution: The use of real-time systems, in particular with stroboscopic features, can successfully be applied for several studies.
- Neutron grating interferometry [7] is now common at some beam lines for the study of the phase contrast and of “dark-field” images, driven by small-angle scattering phenomena and magnetization effects.
- Energy selective imaging enables directly the study of scattering effects near Bragg edges, where a feedback to the crystalline structure in high spatial resolution can be given. In the future, using TOF techniques at the pulsed sources, more information like stress-strain distributions at prominent positions in samples can be obtained. The use of narrow energy bands enables higher quantification accuracy, in particular, in the absorption range at long wavelength.

- Phase contrast imaging in propagation mode helps to enhance material edges by the visualization via refraction artifacts. This mode common in X-ray techniques is not fully developed and exploited with neutrons since beam collimation and coherence is not adequate yet. It has been already shown with very cold neutrons that the edge enhancement is important and can be used for visualization purposes.
- Imaging with polarized neutrons This option is not yet very common since the requirements for components for polarizer-analyzer pairs are quite high. Although some basic tests have been performed successfully [8], dedicated beam lines are rare and the user potential is not yet developed. There is still the need for higher inherent spatial resolution of the used setup option.
- Diffractive neutron imaging combines the direct transmission data on a sample with the scattered component from the beam interaction. In this way, micro-structural information can be obtained and combined with the behaviour on the macro-scale.
- Data fusion between neutron and X-ray image data can be used to enhance and to improve quantitative evaluation and material characterizations. This method needs to have another (X-ray) source in addition to neutrons.

These new approaches are under consideration and development in several laboratories, but not all at the same time. Therefore, it is very important to communicate the latest results on all possible occasions, e.g. web portals, during specialist's meetings like NEUWAVE [9], IAEA organized meetings, etc.

6. Conclusions and Outlook

This short overview about activities in the field of neutron imaging enables us to define the position of each individual facility and their usage. In the same way, it can now be decided which kind of upgrade is reasonable, useful and feasible for the further improvement of the performance and the attraction of more users, both in number and diversity. More advanced methods should be applied and their development should be driven by the user requests (and not for demonstration alone).

It can already be stated that neutron tomography has become a standard tool in several laboratories and n-grating interferometry might be at the same level shortly. The progress with TOF techniques at the new pulsed sources will be demonstrated as soon as these installations become available.

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